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AUTHORS: V.A. Gribkov, G.V. Sklizkov, S.I. Fedotov and A.S. Shikanov

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A HIGH-SPEED OPTICAL SHUTTER FOR FORMING A LASER EMISSION PULSE

by

V.A. Gribkov, G.V. Sklizkov,
S.I. Fedotov and A.S. Shikanov

ABSTRACT

This paper reports on studies on the spatial uniformity and time characteristics of the Kerr cell. It analyzes the optimal construction and electrical parameters of a Kerr cell designed to form light pulses with minimal rise time. The analysis shows it is possible to build a shutter giving a series of light pulses of $\sim 10^{-11}$ sec duration. A Kerr cell with which a light monopulse of 0,4-nsec duration can be obtained is described. Ruby laser light of such duration was used in a design for seven-frame shadow photography of high-speed processes. The seven-frame photograph of a shock wave caused by the expansion of a laser spark is shown.

Electro-optical shutters of the Kerr cell type are widely used in Q-switched lasers for controlling the resonator Q, since they have better high-speed action and are more reliable than Pockels shutters. High-speed Kerr cells have been used to synchronize several lasers, to form coincident light pulses [1,2], for high-speed photography of rapidly developing processes [3], and so on.

It should be noted that in using optical methods (such as shadow photog-

raphy, self-luminance photography and interferometry) to study an object moving with a velocity of ~ 10^7 to 10^8 cm/sec, the spatial resolution is limited basically by the exposure time. Thus, for example, in recording a shock wave passing through a rarefied gas with a velocity $v \sim 3 \cdot 10^7$ cm/sec [1] and an exposure time $\tau \sim 1.5 \cdot 10^{-9}$ sec, the limiting resolution is $d \sim v\tau \sim 0.45$ mm. Therefore, in order to study objects with a resolution of ~ 0.1 to 0.01 mm one must have a light pulse with a duration on the order of 10^{-10} to 10^{-11} sec. In principle, pulses of such duration can be obtained with a mode-locked laser. However, the emission from such a laser consists of a series of spikes with a time interval between spikes on the order of ~ 10 nsec, and in order to use it as a light source for optical research, we must be able to isolate a single pulse from the pulse train with the aid of a Kerr cell [2].

The present work was initiated for the purpose of developing a high-speed Kerr cell with minimal parasitic parameters.

ANALYSIS OF KERR CELL OPERATION

The essence of the Kerr effect consists in the fact that certain isotropic materials, when placed in an electrical field, acquire the properties of uniaxial crystals. The variation in refractive index according to the electrical field is given by the expressions [4]:

$$n_{\parallel} - n_{\perp} = \lambda K E^2 \quad \text{(Kerr law)} \qquad (1)$$

$$n_{\parallel} - n = 2(n_{\perp} - n) \quad \text{(Havelock law)} \qquad (2)$$

where n is the refractive index of a substance in the absence of a field, $n_{\parallel}$ and $n_{\perp}$ are the indices of refraction for the directions parallel and perpendicular to the field, K is the Kerr constant, and E is the voltage of the electrical field.

The transmission of a Kerr cell is expressed by the formula [5]:

$$I = I_p \sin^2 \frac{\delta\varphi}{2} , \qquad (3)$$

$$\delta\varphi = 2\pi K l E^2 ,$$

where I and I_p are the intensities of light passing through and incident upon the shutter, $\delta\phi$ is the phase difference between the two components of the light polarization vector parallel and perpendicular to the field in the Kerr cell, and l is the length of the plate.

Of all the materials which have double refraction in an electrical field, nitrobenzene has the largest Kerr constant. For $\lambda = 0.55\mu$ under normal conditions, the Kerr constant is equal to $K \approx 2.2 \cdot 10^{-5} cm^{-1} V^{-1}$ (sic).* In the range of normal dispersion, the dependence of the Kerr constant on the light wavelength is given by the relationship [6] $K \sim \frac{1}{\lambda}$.

Nitrobenzene is transparent between 400 and 1100 mμ. Figure 1 shows the absorption coefficient of nitrobenzene as a function of the light wavelength [7].

The dielectric constant of nitrobenzene at frequencies up to 10^9 Hz is

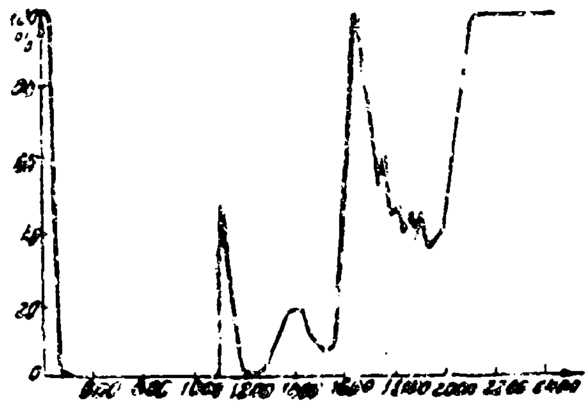

Fig. 1. Nitrobenzene absorption curve. Light wavelength in mμ is plotted along the abscissa, and absorption along the ordinate.

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* Translator's Note: According to the AIP Handbook (2nd Ed., 1963, page 6-187), the Kerr constant of nitrobenzene is actually $3.26 \times 10^{-5} cm/V^2$.

35.7, which is caused by the presence of a constant dipole moment in its molecules. The conductivity of pure nitrobenzene is on the order of $3\cdot10^{-11}\,\mathrm{ohm}^{-1}\mathrm{cm}^{-1}$. The electrical breakdown limit depends on the frequency and lies within the limits of $5\cdot10^{4}$ to $2\cdot10^{5}$ V/cm, but with very short light pulses of $\sim 10^{-9}$ sec may be significantly higher.

In using a Kerr cell in the superhigh frequency range, the problem of the Kerr-effect relaxation time arises. Measurements of the relaxation time of nitrobenzene on the wing of the Rayleigh scattering line [8] showed that the main relaxation processes in nitrobenzene are: (a) the rotational diffusion of anisotropic molecules, and (b) fluctuations in density, which lead in turn to fluctuations of the optical permittivity. Their characteristic times are, respectively, $\tau_{r.d.} \sim 10^{-12}$ sec and $\tau_{f.d.} \sim 5\cdot10^{-11}$ sec.

When using a Kerr cell with a voltage rise time $\leqq 1$ nsec for pulse modulation of light, a number of difficulties connected with its electrical parameters are encountered. In the majority of cases, as a result of the high permittivity of nitrobenzene ($\varepsilon \sim 36$), the capacitance of the Kerr cell is quite high and it may be considered as a purely capacitive load on its power supply generator. In this case, the minimum duration of the electrical pulse front at the plates is determined by the time constant ρC_K, where ρ is the internal resistance of the generator producing the pulses and C_K is the capacitance of the Kerr cell.

The capacitance C_K is composed of the capacitance of the plates and the capacitance of the leads: $C_K = C_p + C_L$. The latter can be reduced to values $\lesssim 1$ cm in practice. The capacitance of the plates is determined by their geometry. For the production of a homogeneous field, the width of the plates must be greater than the distance between them. In order to keep the deviation in the field voltage over an aperture of diameter d (equal to the distance

between the plates) from exceeding 1%, the width of the plates would have to be ≥ 2d. For a phase difference $\delta\varphi$ between components of the light polarization vector, we may write the expression for the capacitance of the plates, using relationship (1), in the form

$$C_P = \frac{\epsilon S}{4\pi d} = \frac{\epsilon l}{2\pi} = \frac{\epsilon\, \delta\varphi}{(2\pi)^2 K E^2}, \qquad (4)$$

where ε is the permittivity and K is the Kerr constant of nitrobenzene, S is the area of the plates and E is the voltage of the electrical field. When $\delta\phi = 2\pi$, $\lambda = 6943$Å and $E = 5\cdot10^2$ cgs esu, the values for the capacitance of the plates and the total capacitance are $C_p = 1$ cm and $C_K \approx 2$ cm, and the time constant of the Kerr cell for $\rho = 8.3\cdot10^{-11}$ cgs esu (75 ohms) amounts to $\rho C_K \sim 1.6\cdot10^{-10}$sec.

In order to form light pulses with minimum amplitude rise time, it is necessary to obtain the maximum rate of change of the phase difference between components of the polarization vector at the output of the Kerr cell. To estimate what is possible, let us assume the driving electrical field has the form of an instantaneously activated voltage U_0 at the moment of time t = 0. It is clear that the form of the voltage on the plates of the Kerr cell is

$$U = U_0(1 - e^{-t/\rho C_K}) \; . \qquad (5)$$

Using Eq. (3) for the phase difference and its derivative, we can write the expressions:

$$\delta\varphi(t) = 2\pi K l \frac{U_0^2}{U^2} (1 - e^{-t/\rho C_K})$$

$$\delta\dot{\varphi}(t) = \frac{4\pi K l U_0^2}{d^2 \rho C_K} (1 - e^{-t/\rho C_K})\, e^{-t/\rho C_K} \; . \qquad (6)$$

From the last expression we can obtain a value for the maximum rate of change in the phase difference:

$$\delta\dot{\varphi}_{max} = \frac{\pi K l U_0^2}{l^2 \rho C_K} \; . \qquad (7)$$

This value is reached at the moment of time

$$t = \rho C_K \iota n^2.$$

Disregarding the capacitance of the leads, when $C_K = C_n = \frac{\epsilon l}{2\pi}$ we have

$$\delta\dot{\varphi}_{max} = \frac{2\pi^2 K E_0^2}{\rho\epsilon}. \qquad (8)$$

Thus, for $K = 2.2 \cdot 10^{-5}$; $E = 10^3$; and $\rho = 1.1 \cdot 10^{-11}$ (ρ = 10 ohms), we obtain $\delta\dot{\varphi}_{max} = 1.1 \cdot 10^{12} sec^{-1}$.

If the voltage amplitude U_0 is large enough that the phase difference between components of the polarization vector significantly exceeds 2π, then a beam of light passing through a Kerr cell placed between two crossed polarizers appears to be modulated according to a law determined by Eq. (3), from which it is evident that the light will consist of a series of spikes, and the length of the entire series will equal the duration of the voltage rise front in the Kerr cell.

Let us determine the duration τ of the first spike after t = 0. From (3) it follows that $I = 0$ for $K\iota E_0^2 = N$, where N is an integer and the voltage is $E_0 = U_0/d$. Using Eq. (5), we may write

$$K\iota E_0^2 (1 - e^{-\tau/\rho C_K})^2 = 1.$$

whence, for $N >> 1$, we obtain

$$\tau = \frac{\rho\epsilon\iota^{1/2}}{2\pi K^{1/2} E_0}. \qquad (9)$$

From the last expression it follows that when $K = 2.2 \cdot 10^{-5}$; $E = 10^3$; $\rho = 1.1 \cdot 10^{-10}$ (ρ = 10 ohms); ι = 1 cm; and ϵ = 36, the duration of the first spike is $\tau \approx 1.3 \cdot 10^{-11}$sec.

It should be noted that these estimates were made without consideration of the finite time required for the light to pass through the Kerr cell, which may have some effect on the duration of the spike.

CONSTRUCTION OF THE KERR CELL

A Kerr cell is usually made in the form of a flat condenser, placed in a glass cuvette with nitrobenzene. Certain difficulties are encountered in reducing the stray capacitance when the construction is designed for high-speed operation, since the necessary high voltage insulation requires lengthening the electrical leads from the condenser plates. In our case, the cuvette containing the nitrobenzene was made of metal and served as one of the electrodes.

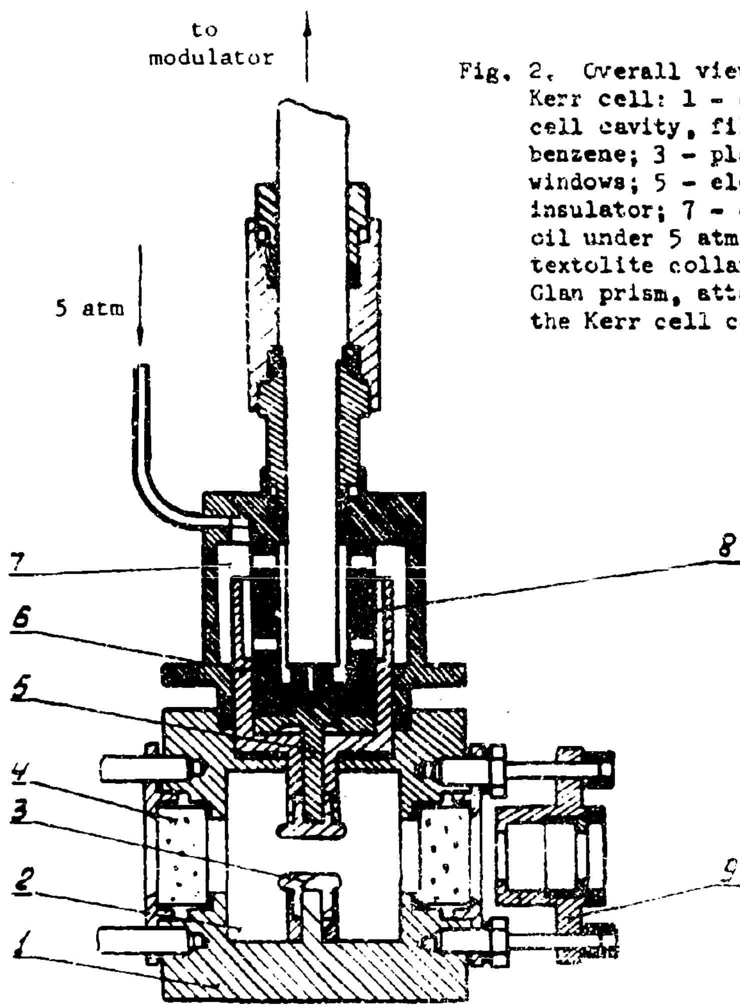

Fig. 2. Overall view of high-speed Kerr cell: 1 - cell casing; 2 - cell cavity, filled with nitrobenzene; 3 - plates; 4 - optical windows; 5 - electrode; 6 - teflon insulator; 7 - cavity filled with oil under 5 atm pressure; 8 - textolite collar; 9 - holder for Glan prism, attached directly to the Kerr cell casing.

Figure 2 shows an overall view of the Kerr cell. The lower plate is attached directly to the casing, while the upper one is attached to the insulator, through which the high-voltage electrode passes. The high-voltage lead and the external part of the insulator are filled with pure transformer oil. The capacitance of the Kerr cell leads in this construction is $C_L \sim 2$ nF with an inductance of $L \sim 3$ nH. Since the insulator also serves as a gasket to separate the oil from the nitrobenzene, extreme care must be used in its manufacture, because the slightest penetration of one liquid into the other makes the Kerr cell completely unsuitable for operation. Just as much care must also be exercised in finishing the metal surfaces which will come into direct contact with the teflon. The criterion for good assembly of a Kerr cell is the complete absence of any odor of nitrobenzene. In the Kerr cell used in the resonator, the plates have dimensions of 20 x 40 mm^2, while in the cells used for pulse sharpening the plates have dimensions of 12 x 12 mm^2. The dimensions of the inner cavity of the metal casing were chosen such that, on the one hand, the distance of all points on the high-voltage electrode from the casing would be as large as possible, to increase the capacitance of the casing electrode; and on the other hand, as small as possible in order to decrease the inductance of the leads. According to our estimates, this distance must be on the order of 1.5 d. All current-carrying surfaces were silvered and carefully polished. Although the presence of the silver also increases the conductivity of the nitrobenzene, when using a Kerr cell to control voltage pulses of $\sim 10^{-7}$ sec in duration, studies on the space-time parameters of the Kerr cell show no irregularities in the optical properties of nitrobenzene caused by the passage of a current through the Kerr cell.

SPATIAL UNIFORMITY OF THE KERR CELL

A study of the spatial uniformity of the light field, which is determined

by the uniformity of the electrical field between the plates, was performed by a shadowgraph method with crossed polarizers. A diagram of the experiment is shown in Fig. 3. The light beam was produced by a Q-switched ruby laser, in which the resonator was switched by another Kerr cell; the energy was 0.5 J and the pulse duration was 40 nsec. The amplitude of the controlling electrical pulse in the

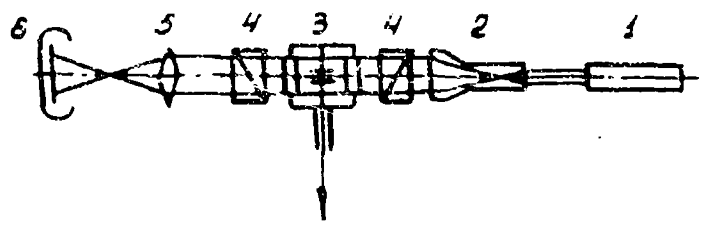

Fig. 3. Plan of experiment for shadow-method investigation of the spatial uniformity of the inter-electronic space of a Kerr cell at the moment an electrical pulse is fed to it: 1 - Q-switched ruby laser; 2 - collimator; 3 - Kerr cell; 4 - Glan prisms; 5 - objective, 6 - photographic plate.

Kerr cell to be studied was chosen such that the phase difference of the vector components of the polarization of light passing through the cell would change by 2π during the voltage rise front on the cell plates. The moment the voltage was fed to the Kerr cell coincided with the maximum intensity of the ruby laser beam. The characteristic shadowgraph is shown in Fig. 4. The least darkening is observed in the middle part, between the plates, and is determined by the minimal exposure time, equal to the voltage pulse front duration $\tau \approx 1.5$ nsec. The significant darkening at the edges and near the surface of the plates is caused by incomplete closure of the shutter for a change in the phase difference by an amount less than 2π in the first case, and, in the second case, by an amount greater than 2π, due to an increase in the field voltage as a result of the localization of impurity particles near the surface of the plates.

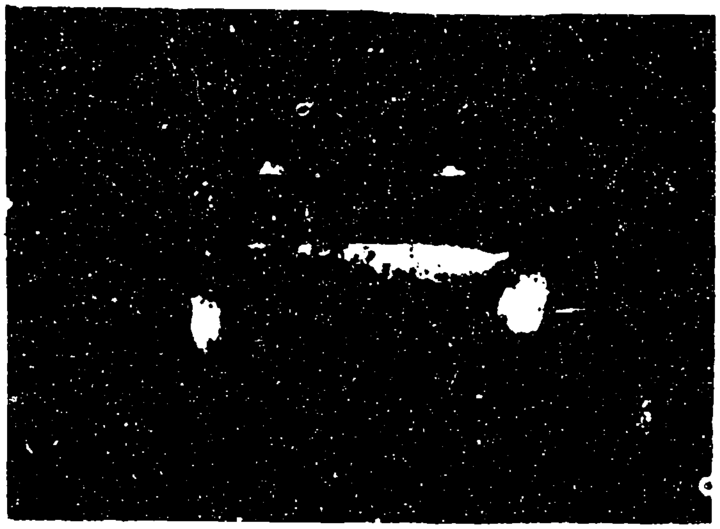

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Fig. 4. Shadowgraph showing the transmission of a Kerr cell, viewed in beam cross section (polarizer and analyzer crossed).

In order to eliminate the question of whether schlieren distortions occur in nitrobenzene under the influence of a varying electrical field, shadow photography of the cell was performed by the Töpler method, using a single optical knife with two different positions of its edge -- parallel and perpendicular to the direction of the electrical field. Figure 5 shows the characteristic schlieren photographs, from which it may be seen that during the time the electrical pulse is applied to the Kerr cell ($\sim 10^{-7}$sec), no significant schlieren inhomogeneities appear.

Fig. 5a

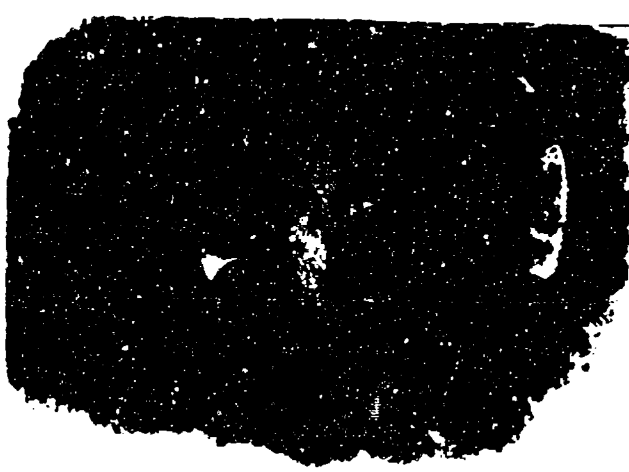

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Fig. 5b

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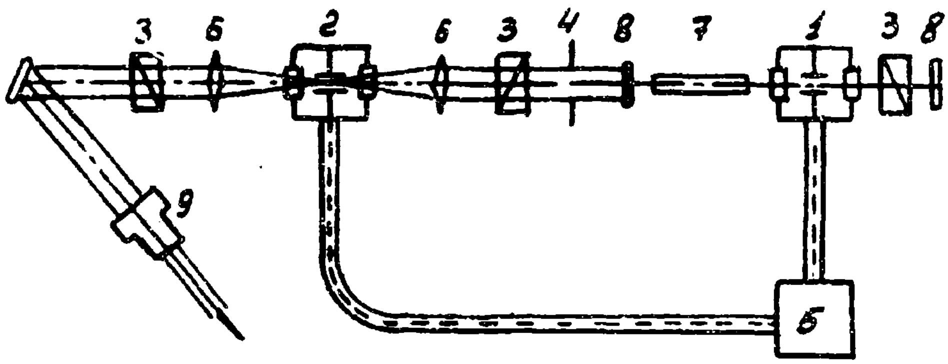
Fig. 5. Characteristic schlieren photographs of the inter-electrode space of a Kerr cell at the moment of feeding it the electrical pulse. Exposure time of the frame is ~30 nsec: (a) - Edge of the optical knife placed orthogonal to the vector of the electrical field voltage within the Kerr cell; (b) - Edge of the optical knife rotated by 90°.

INVESTIGATION OF THE TIME PARAMETERS OF THE KERR CELL

The operating time of the Kerr cell was determined by the duration of the light pulse formed by it, as shown in the diagram of Fig. 6. In the chopping cell 2, we used plates with dimensions of 12 x 12 mm^2, and the distance between them was chosen such that the phase difference between polarization vector components at the front of the electrical pulse amounted to 2π. In order to eliminate the effect of the non-uniform electrical field near the surface of the plates, the laser beam was focused in the space between the plates by a lens with a focal length of f = 200 m (sic). The beam diameter within the Kerr cell was significantly less than the distance between the plates. The form of the light pulse at the output of the sharpener (consisting of the crossed polarizers 3 and the Kerr cell 2) was recorded on an I-2-7 high-speed oscillograph with the aid of the coaxial photodiode 9. With an electrical voltage amplitude of U_0 = 25 kv, a front duration of 0.5 nsec and a distance between plates of 4 mm, the duration of the light pulse at the output



to oscillograph

Fig. 6. Plan of apparatus for forming a laser emission pulse with the aid of a high-speed Kerr shutter: 1 - Kerr cell used for Q-switching the ruby laser; 2 - high-speed Kerr cell; 3 - Glan prisms; 4 - diaphragm; 5 - generator for high-voltage nanosecond pulses, used to drive the Kerr cells; 6 - lenses; 7 - ruby crystal; 8 - mirror of optical resonator; 9 - coaxial photodiode (FEK-15).

amounted to $\sim 1{,}5$ nsec. The characteristic oscillogram of the pulse is shown in Fig. 7.

Using the same Kerr cell, measurements were made of the value of $\delta\dot{\phi}_{max}$. The lay-out of the experiment was practically identical to that shown in Fig. 6, except that the distance between the plates was 2 mm, corresponding to an

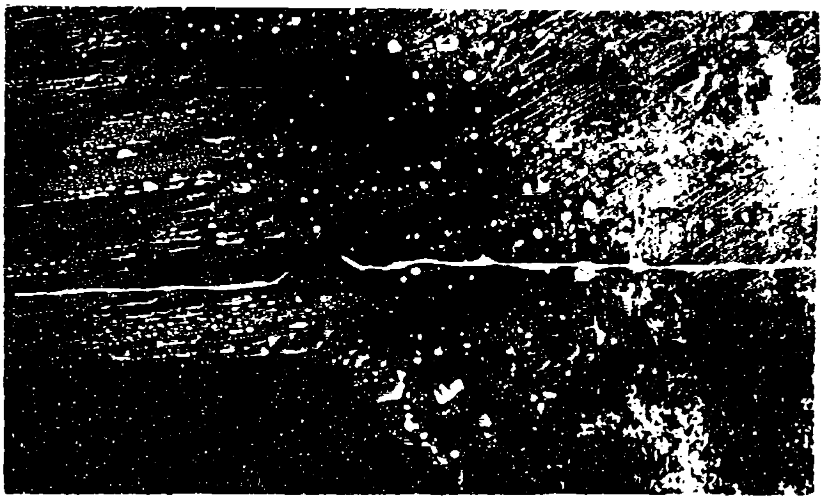


Fig. 7a

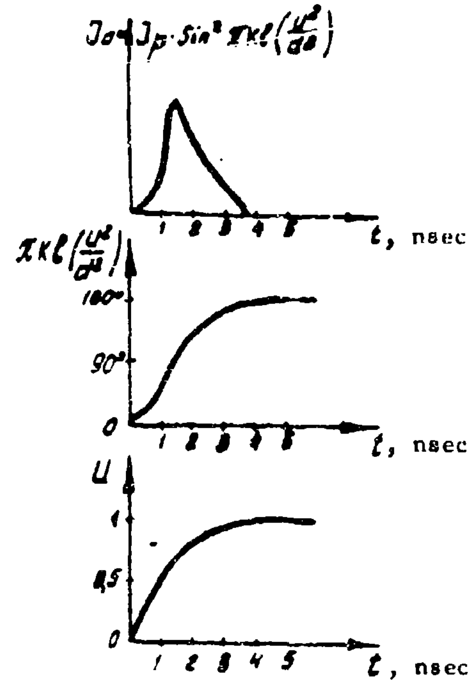


Fig. 7b

Fig. 7. (a) Oscillogram of light pulse at output of Kerr shutter for a change in the phase difference $\delta\phi$ by 2π; (b) Determination of the form of the electrical pulse rise front from the form of the light signal.

electrical field voltage in the cell of ~ 400 cgs esu. The total change in the phase difference at the front of the electrical pulse therefore amounted to 9π; thus, at the output of the sharpener the light was chopped into a series of four spikes. The characteristic oscillogram of this type of light pulse is shown in Fig. 8. The value of $\delta\dot{\phi}_{max}$ was determined from the relationship $\delta\dot{\phi} = 2\pi/\tau$, where τ is the duration of the first spike on the base, and amounted to $2\cdot10^9$ sec^{-1}. The calculated value of $\delta\dot{\phi}_{max}$ for the given geometry of the plates is equal to $\delta\dot{\phi}_{max} \sim 3\cdot10^9$ sec^{-1}.

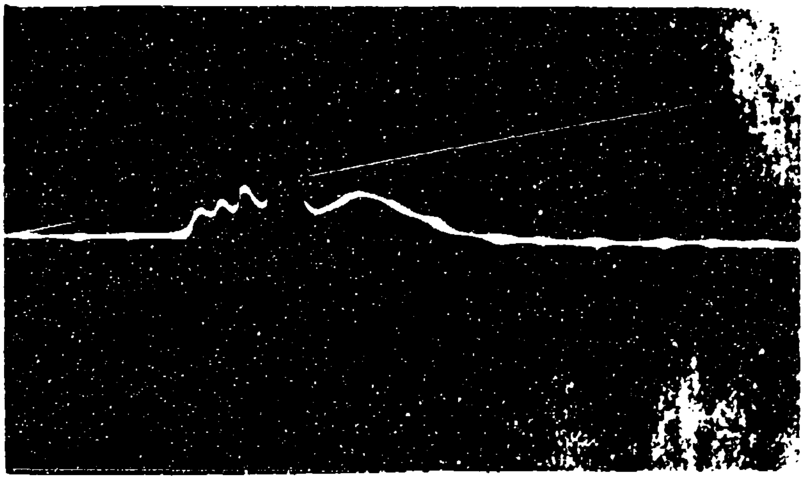


Fig. 8. Characteristic oscillogram of a series of light pulses obtained by means of a Kerr shutter, for a change of 9π in the phase difference between components of the light polarization vector.

The technique of pulse modulation of light by the front of an electrical pulse, for all its relative simplicity, nevertheless possesses a number of serious shortcomings. These are, first, the difficulty in obtaining a minimal transmission on the flat part of the controlling pulse, and second, the need for establishing a high degree of uniformity in the electrical field in the Kerr cell; this imposes a limitation on the value of the capacitance C_K and, consequently, on the limiting duration of the light pulse. In this respect the

method of modulating with a short electrical pulse appears to be significantly more advantageous.

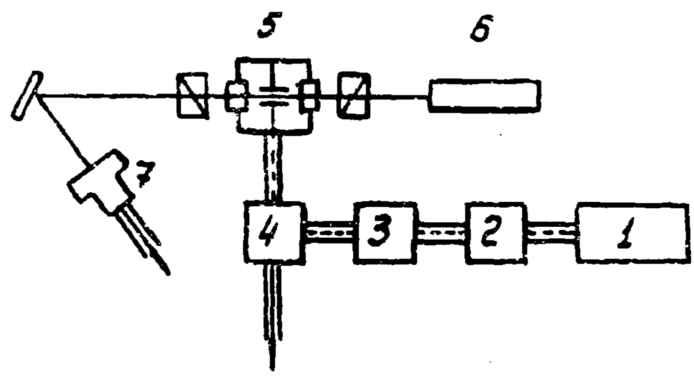


Fig. 9. Plan of apparatus for modulation of light with an ultrashort electrical pulse:
1 - generator for high-voltage nanosecond pulses, with the following parameters: $U_{max} = 50$ kV; $\tau_i \approx 2 \cdot 10^{-7}$sec; $\tau_f \approx 2.3 \cdot 10^{-9}$sec;
2 - nanosecond pulse sharpener, which shortens the duration of the pulse front to a value of $\tau_f \approx 0.4 \cdot 10^{-9}$sec;
3 - differentiating element used to form a pulse with a half-intensity duration of $0.5 \cdot 10^{-9}$sec;
4 - capacitive divider;
5 - Kerr shutter;
6 - Q-switched ruby laser;
7 - coaxial photodiode (FEK-15).

Modulation of this type was achieved by the technique illustrated in Fig. 9. The formation of a short electrical pulse was made in the following manner. The leading front of a pulse from a high-voltage square-pulse generator (1), with a duration of $\tau_f \sim 2$ nsec, was shortened by a sharpener (2) to a value of $\tau_f \sim 0.4$ nsec. The pulse was then differentiated by means of a coaxial differentiating section (3), forming at its output a positive pulse with a duration approximately equal to the duration of the leading front with an exponential drop. The form of the pulse at the output was recorded with the aid

of a capacitive divider (4). The characteristic oscillogram is shown in Fig. 10a.

a)

10 nsec

b)

10 nsec

Fig. 10. (a) Characteristic oscillogram of electrical pulse after differentiating section; (b) characteristic oscillogram of light pulse at output of Kerr shutter when electrical pulse shown in Fig. 10 (a) is fed to plates of the cell.

In order to transmit this sort of pulse to the plates of the Kerr cell without any significant distortions, the capacitance of the differentiating section C_d must be greater than the capacitance of the cell and, at the same time, must satisfy the condition $2\rho C_d \lesssim 4 \cdot 10^{-10}$ sec, where ρ is the wave impedance of the cable. For $\rho = 75$ ohms, $C_d \sim 2$ nF and, consequently, the capacitance of the Kerr cell must be on the order of $C_K \lesssim 2$ nF.

In the Kerr cell (5) we used 3 x 4 mm plates set ~ 1.5 mm apart. The

total capacitance of the cell was therefore $C_K \sim 4$ nF, and the capacitance of the differentiating section C_d was ~ 2 nF. With such a ratio of capacitances, the pulse in the Kerr cell was integrated and its amplitude at the plates was approximately 4 kV. The maximum phase difference was thus $\sim \pi/6$, which corresponds to a shutter transmission of $\sim 25\%$.

An oscillogram of the light pulse is shown in Fig. 10b. The duration between its half-intensity points is 0.5 nsec. It should be noted, however, that this value represents the upper limit, since the duration of the recorded pulse is about at the limit of resolution of the coaxial photodiode.

APPLICATION OF THE KERR CELL TO HIGH-SPEED PHOTOGRAPHY

The high-speed Kerr cell may be used as an optical shutter to obtain a series of short (up to 10^{-10}sec) pulses. A shutter of this type, in combination with linear image scanning in multistage image converter tubes, makes it possible to obtain a multi-frame photography of weakly luminous objects with an exposure equal to the duration of the pulse. When a laser is Q-switched by a Kerr cell which is fed with a sequence of electrical pulses, the emission from this laser represents a series of regular nanosecond pulses with a time interval between them on the order of tens of microseconds. Such a laser may be used for stroboscopic photography of periodic processes [9], and may also be combined with a high-speed photorecording camera of the "rotating mirror" type for recording rapid-action processes [10].

As another application of the Kerr cell, we may mention its use for shortening a laser pulse to be used for photographing plasma plumes obtained at the focus of another laser. In Ref. [1], this was used to obtain five-frame shadow interferometric and schlieren photographs with an exposure of 3 nsec and a delay between frames of 40 nsec.

In the present work, an improvement in the construction of a Kerr cell

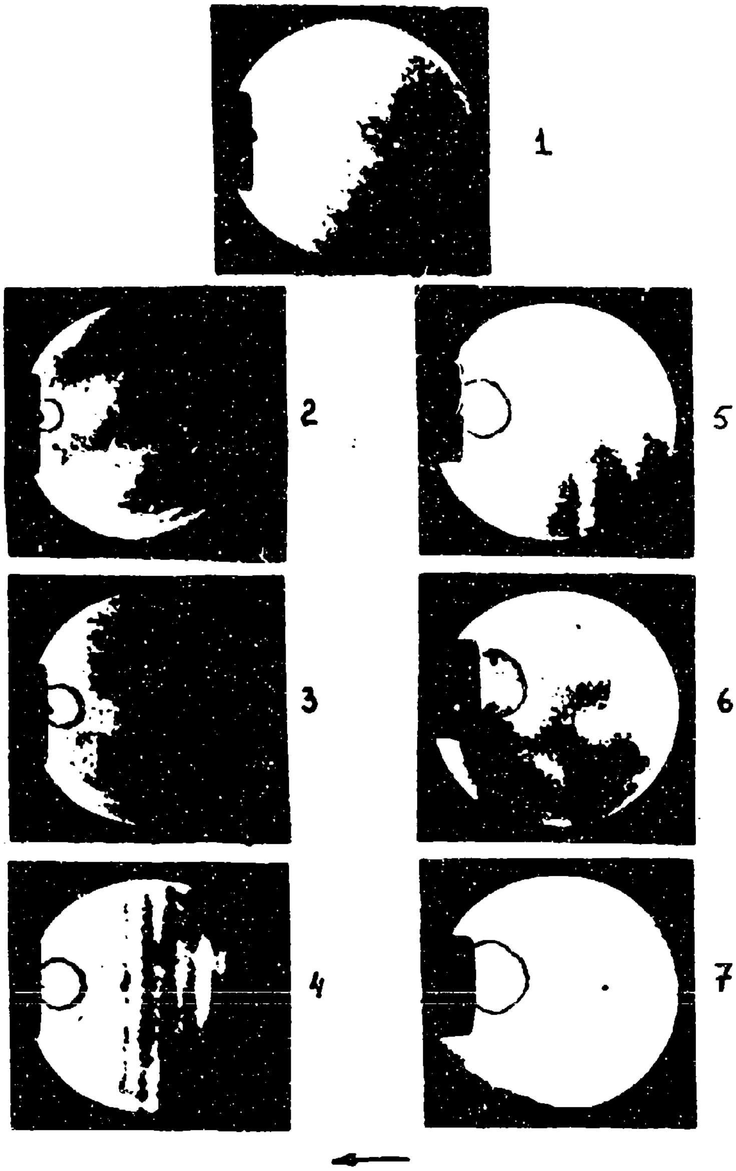


Fig. 11. High-speed seven-frame shadowgraph of shock wave in air at pressure of p = 0.4 mm Hg, formed by expansion of laser "spark". Exposure of each frame was $1.5 \cdot 10^{-9}$sec; interval between frames was $36 \cdot 10^{-9}$sec. The arrow indicates direction of the neodymium laser beam.

permitted a shortening of the exposure time. Figure 11 shows the seven-frame shadowgraph of a shock wave in the light of a ruby laser. The interval between

frames was 36.6 nsec. The duration of the pulse from the ruby laser after sharpening, measured between the half-intensity points, is ~ 1.5 nsec, and at half-power, ~ 2 nsec, which ensures an exposure time per frame of ~ 2 nsec. The shock wave was formed by the expansion of a spark created when the beam of a Q-switched neodymium laser was focused on the surface of a carbon fiber placed in a vacuum chamber. The residual air pressure was ~ 0.4 mm Hg. The radiant energy of the neodymium laser was ~ 1.5 J, and the duration of its pulse at the half-intensity point was ~ 15 nsec. The beam was focused by a lens with a focal length of f = 100 mm, so that the diameter of the focused spot was ≈ $3 \cdot 10^{-2}$cm, and the radiation flux density was ~ 10^{-11} W/cm^{-1}.

The first frame of the photograph corresponds to the moment when the amplitude of the neodymium laser striking the target is at its maximum. In this frame, we see a non-transparent region near the surface of the target, with a characteristic dimension of ~ 0.2 cm. After the end of the pulse, the plasma begins to expand adiabatically, forming thereby a shock wave in the residual-gas atmosphere. The shock wave with its sharp front is clearly visible in the second and all following frames. The initial velocity of the shock wave, as determined from the photograph, is ~ $6 \cdot 10^6$cm/sec. The shock wave has a distinctly pronounced spherical shape. A significant deceleration is observed as it expands, so that after ~ 150 nsec, which corresponds to the seventh frame, the velocity is ~ $3 \cdot 10^6$cm/sec.

In addition to solving optical problems, the high-speed Kerr cell may find application in studying the parameters of high-voltage electrical pulses on a load, in determining the time resolution of measuring circuits for short light signals, and so forth. We have used a Kerr cell to determine, from the form of the light signal passing across the cell through crossed polarizers, the form of the electrical rise front on the plates of the Kerr cell. Calculations were

made with the aid of Eq. (3), and the result is shown in Fig. 7b, in the form of the curves $\delta\phi = \delta\phi(t)$ and $U = U(t)$. The duration of the electrical pulse front $\tau_{0,d}$ was determined from Fig. 4b to be 2.3 nsec. The calculated value of $\tau_{0,d}$ is 2.1 nsec.

In conclusion, the authors express their deep appreciation to Academician N.G. Basov for his constant attention to their work, and to O.N. Krokhin for discussing the results.

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